Chapter 8

PATTERNS OF ENERGY SUPPLY AND USE

What are the present patterns of supply and demand for energy? Can the requirements for different forms of energy be met in more efficient ways or by using alternative energy sources? If such sources are to be used on a large scale, what problems have to be overcome?

8.1 Having examined energy use sector by sector in chapter 6 and energy sources that might provide alternatives to fossil fuels in chapter 7, we now take a broader look at the energy system. In this chapter we discuss the present patterns of demand and supply for the three main forms in which energy is required, and possible alternative patterns. Those forms of energy are heat (8.4-8.16), propulsion for transport (8.17-8.25) and electricity (8.26-8.54). In the final section of the chapter we consider some cross-cutting and fundamental issues about storing energy and using energy carriers (8.55-8.65). This analysis provides the basis for the following chapter, in which we present illustrative scenarios for the UK energy system in 2050. It is also informed, in turn, by some of the results from that exercise.

8.2 The aspect of energy policy that has received most attention, both from governments and in public debate, is alternative ways of generating electricity. What may be more difficult to replace is the use of fossil fuels to provide heat and propulsion for transport.

8.3 Demand for primary energy is affected not only by demand from final users, but also by the overall efficiency of the energy system in matching the forms, times and locations in which energy is required with the forms, times and locations in which it is available. Energy losses within the system accounted for 30% of the UK's demand for primary energy in 1998, even without taking complete supply chains into account (see figure 5-I).[1] In particular, electricity generation usually involves the loss of large amounts of energy in the form of waste heat, as explained previously (3.39 and box 3A), and further losses occur in the course of transmission and distribution. The combined effect is that, whereas about one-sixth of the energy supplied to final users in the UK is in the form of electricity,[2] providing that electricity requires almost one third of the primary energy used in the UK.[3] In looking at requirements for particular forms of energy, we also consider whether there are ways in which the overall efficiency of the energy system could be improved. This might have major implications for the UK's ability to achieve very large reductions in carbon dioxide emissions over the next half century.

HEAT

8.4 In 1994, the most recent year for which figures are available, energy used for heating was, at 36%, the largest component of UK energy consumption by end use.[4] About 80% of energy used in the household sector, 75% in industry, and 65% in other non-transport uses is devoted to the provision of heat.[5] At present the greater part of that energy is provided by fossil fuels, the remainder by electricity.

8.5 Part of the demand from industry, at an average rate of 16 GW at present, is for heat at high temperatures for use in particular processes *(high-grade heat).* This will continue to be provided by fossil fuels for the foreseeable future. It would be technically feasible to provide some of it by using energy crops or agricultural and forestry wastes as fuel, but that is unlikely to happen so long as other sources are available. Landfill gas is technically suitable for the purpose, but cannot be regarded as a source of energy in the longer term (7.80).

8.6 The greater part of the demand is for *low-grade heat* for industrial processes such as drying, and to maintain the temperature in buildings and heat water for domestic and other purposes. At the same time very large quantities of energy are being wasted because the greater part of the energy content of fuels used to generate electricity emerges as low-grade heat and is not at present put to use. In view of the importance of heat as a component of energy demand, and the scale on which it is being wasted at present, **the UK must develop a comprehensive strategy for the supply and use of heat.**

8.7 A more efficient way of using the energy in fuels is to burn them in combined heat and power plants (3.40) to provide both heat and electricity. Such plants have been used much more extensively in some other countries, notably in Scandinavia. In the UK they have hitherto predominantly served industrial sites with a large demand for low-grade heat. They declined in importance during the 1970s and 1980s,[6] but are now being promoted by entrepreneurial companies which have emerged following liberalisation of the electricity and gas markets, in some cases as subsidiaries of large energy companies (5.20). The commercial attractions of investing in a combined heat and power (CHP) plant have depended on the relative prices of gas and electricity and the terms on which top-up electricity can be bought from the grid and (not permitted until 1989) surplus electricity sold to the grid. It is only recently that the government has recognised the desirability from a national viewpoint of increasing the overall efficiency of energy conversion, and has adopted policies to encourage the wider use of CHP plants and set a target (5.45). There is a strong case for a much wider development of combined heat and power schemes for both the industrial and the domestic market. There are many opportunities in both the industrial (6.18) and services (6.41) sectors.

8.8 Using CHP plants to supply the needs of households entails either installing a separate plant in each dwelling or constructing networks to distribute the heat. Designs to serve individual dwellings have been developed, roughly the size of a domestic boiler, though much more complex, and fuelled by gas. There has been little progress as yet towards marketing such devices in the UK, despite much research and development by British Gas covering both fuel cells and microturbines.[7] A design using a fuel cell has been installed on a pilot scale in Germany.[8] There is a widespread expectation that within 20 years many households will have equipment of this kind.[9] With very large reductions in carbon dioxide emissions there might be sufficient fossil fuels available in 2050 to enable some households to have such plants, but certainly not all households. In the very long term such devices might be fuelled by hydrogen, produced using energy from sources other than fossil fuels (8.60-8.61).

8.9 Local distribution networks for heat are a more firmly established technology. Almost unknown in the UK, they are a familiar feature in Scandinavia, where networks can now convey heat economically over tens of kilometres. Box 8A describes systems which serve Stockholm and the surrounding area. Normal domestic central heating systems are supplied from the high-pressure system through heat exchangers, and individual households charged according to the metered amount of heat used.[10] There is likely to be major growth in small heat and power schemes serving blocks of flats (6.56), but it is unlikely that extensive schemes will be undertaken in the UK unless there is much stronger support from government. **We recommend that the UK government and devolved administrations carry out detailed studies to identify the most effective ways of promoting and facilitating the large-scale growth of heat networks.**

8.10 Heat networks become even more attractive as a method for reducing carbon dioxide emissions if heat can be obtained from sources other than fossil fuels. Most of the energy sources which are alternatives to fossil fuels cannot supply heat except indirectly, by first generating electricity. Nuclear power stations produce very large quantities of waste heat but it is likely to be impracticable to make any use of it, unless new stations were to be constructed under different siting criteria, and probably also on a much smaller scale than existing stations. Geothermal energy can supply heat, but the amount exploitable in the UK with presently foreseeable technology is very limited.

BOX 8A MORE INTELLIGENT USE OF HEAT[11]

Large-scale heat distribution networks are found in many Scandinavian towns and cities. They are generally supplied by combined heat and power (CHP) plants, and frequently these burn wastes from the region's large forestry industry.

Stockholm has three large networks operated by Birka Energi, a company owned by the municipality and a Finnish group. These serve most of the blocks of flats in the city as well as many commercial and public buildings. These networks extend to communities outside the capital, as useful heat can be delivered 40 kilometres from the source.

One of these three networks, serving the centre of the city, is supplied partly by a large, coal-burning CHP plant and partly by heat pumps. The second, serving the south of the city, is supplied by the world's largest heat pump system at Hammarby and by a nearby CHP plant burning municipal waste. The electrically powered heat pumps supply on average some 70% of the heat. The third system, in the western districts of Stockholm, burns biofuels.

The main source of heat harnessed by the heat pumps is municipal wastewater. The temperature of this ranges from 5°C in winter to 22°C in summer. The heat pumps extract heat from the wastewater arriving at a large sewage works and use this to raise the temperature of the pressurised water in the heating network to 60-90°C. After delivering heat to hundreds of buildings, this water returns to the heat pump at a temperature some 30°C lower. Another source of heat is seawater from the Baltic. The system supplies about 3.5 times as much energy as it consumes in electricity. During periods of extreme cold, when the heat pumps cannot supply sufficient heat, the network is topped up by burning oil and by using electricity for direct heating of the water.

The use of heat pumps on this large scale in Stockholm and some other Swedish cities stems in part from the oil crisis of the 1970s, which pushed up the cost of oil as a fuel for heating, and in part from an abundant supply of relatively cheap electricity generated by nuclear and hydroelectric plants.

Replacing fossil fuel-fired heating systems with systems based on electrically-powered heat pumps will reduce total carbon dioxide emissions if a substantial proportion of the electricity used is generated by non-fossil fuel sources. In Sweden that is the case. In the UK, most electricity is generated by burning fossil fuels; at present heat pumps would reduce carbon dioxide emissions only by comparison with oil- or coal-fired boilers. However, as the proportion of electricity generated by non-fossil fuel sources rises, there will be a growing potential for reducing carbon dioxide emissions by replacing fossil fuel-fired heating plants with heat pump systems.

8.11 The most readily available alternative sources for heat are carbon-based: energy crops, agricultural and forestry wastes, and municipal wastes. Although their use gives rise to carbon dioxide emissions, these are largely balanced by the carbon dioxide removed from the atmosphere by growing vegetation within a managed rotation, or in the case of municipal waste by preventing more damaging emissions of methane.[12] Until the last decade these alternative carbon-based sources provided more energy in the UK in the form of heat than in the form of electricity. Subsequently the position has been distorted by the non fossil fuel obligation; government policy has treated them as primarily fuels to generate electricity. That distortion should be corrected for the future. **Energy crops and wastes should be regarded in the medium to long term as having a premium role in supplying heat. They should be used in plants providing both heat and electricity to an urban area, and located close to the sources of the fuel in order to minimise transport.** Although all forms of waste should be utilised as energy sources to the extent that they continue to be available, the major long-term potential is in energy crops.

8.12 CHP plants vary in their heat-to-power ratio. The ratio in older plants was typically about 4:1. More recent plants, designed to maximise the amount of electricity generated, may have ratios as low as 2:1, and less flexibility to vary the ratio. **CHP plants should be regarded primarily as a source of heat. It may be desirable to keep a large part of their capacity to generate electricity in reserve, so that it can be used at those times at which there is a shortfall in supply from other sources.** If combined heat and power plants are viewed in that light, it would be preferable to design them as steam-cycle plants, rather than as combined cycle plants employing pyrolysis (7.56). The latter have a higher efficiency in terms of generating electricity but may have a lower overall efficiency, and offer less flexibility to vary the heat-to-power ratio. They therefore represent a less effective way of limiting carbon dioxide emissions.

8.13 The concept of regarding CHP plants as providing primarily heat is already well established in Denmark, where there is widespread use of district heating plants, sometimes fuelled by straw or wood.[13] During the summer, when demand for heat is substantially reduced, some plants are closed and electricity provided from other sources, including wind turbines. In some cases the generating capacity of such plants is being used to cover shortfalls in the supply of electricity from wind turbines.[14]

8.14 If the aggregate amount of energy that can be obtained in future as low-grade heat from fossil fuels and alternative carbon-based fuels is not sufficient to meet demand, the gap would have to be filled by electricity. Moreover, even with very extensive development of district heat networks, a substantial proportion of buildings would not be within reach of a district heat network, and for many of them use of gas might not be practicable; electricity, in contrast, is universally available. Conventional methods of electric heating for buildings are both more expensive than gas and, with the present mix of energy sources for electricity generation in the UK, give rise to two and a half times as much carbon dioxide for each unit of heat supplied (6.80).[15] However, the amount of heat that can be obtained from a given quantity of electricity is tripled if it is used to drive heat pumps (see box 3A), rather than provide heat directly. **To improve energy efficiency, government should promote use of heat pumps wherever electricity has to be used to supply low-grade heat.** Heat pumps can be used as the source of supply for heat networks (box 8A provides an example). On the basis of the UK's current mix of fuels to generate electricity, there would not be any advantage in terms of reduced carbon dioxide emissions in using heat pumps in preference to high-efficiency gas boilers. If however electricity comes to be generated predominantly from sources that do not give rise to carbon dioxide emissions, its use to drive heat pumps becomes much more attractive.

8.15 The purpose of the strategy for heat we are advocating is not only to increase the efficiency of supply, but also to obtain radical reductions in the demand for energy for heating. **A central policy objective must be a very large reduction in demand for energy for heating and cooling, achieved through much more sophisticated management of heat and much wider use of combined heat and power schemes for both the industrial and the domestic market. The resulting heat networks, supplied initially by fossil fuels, could ultimately obtain heat from energy crops and electrically powered heat pumps.** The general warming of the climate may make some contribution to this objective; but, without an intelligent policy response, any advantage in that respect might be outweighed by the growing demand for energy for cooling.

8.16 Greatly improved management of heat will require modifications on a massive scale, both to individual buildings and to the infrastructure of neighbourhoods. There will have to be not only a much higher standard of insulation in buildings but also a much more sophisticated approach to heat management, taking full advantage of microelectronics. Buildings must be designed to make full use of solar energy, both through passive heat gain by the building structure and through use of solar panels to heat water. The requirement for cooling in all types of building should be an integral part of the strategy right from the beginning, and heat exchangers should become a standard design feature in buildings of all types.

PROPULSION FOR TRANSPORT

8.17 Energy demand for transport is not only very substantial, but has grown rapidly. Oil at present supplies 99% of the energy used for transport in the UK, with almost all the rest provided by electricity.

8.18 Achieving a reduction in energy demand for transport over the next half century will require both radical changes in technology and effective and thoroughgoing implementation of integrated transport policies that will reduce the overall energy intensity of the transport system. This will involve reducing the need for mobility and making increasing use of modes which use less energy than private road transport. The Commission has explored these issues in previous reports (6.125 and box 6D).

8.19 Whatever degree of success is achieved in that direction, there will remain a very large demand for a readily portable energy source with a high energy density and power density suitable for propelling personal vehicles. It will be technically difficult to replace fossil fuels in that role, and for the time being it is likely to remain necessary to treat transport as the premium use for oil. The main emphasis in policy over coming decades therefore must be on finding ways of using fossil fuels in transport that reduce the amounts of carbon dioxide emitted. There have been big improvements in the conversion efficiencies of internal combustion engines. In the case of personal vehicles however these have been offset hitherto by increases in the size and weight of vehicles and in their ancillary equipment (6.115). European car manufacturers have entered into an agreement with the European Commission to reduce average carbon dioxide emissions per kilometre for new cars by 2008 (6.123). One immediate option for doing so is to switch between different forms of fossil fuel. However the implications for health-related pollutants such as particulates also have to be taken into account.

8.20 The Commission's reports on transport drew attention to the advantage that could be obtained (at that time assessed as a reduction of 20-30% in carbon dioxide emissions) if petrol were to be replaced by diesel as the fuel for cars and the smallest goods vehicles. Because of concern about health effects however they did not favour a major shift to diesel until more stringent limits had been placed on emissions of particulates and nitrogen oxides. Progress towards more stringent standards for emissions from diesel engines and improved technology to meet them has been slower than the Commission hoped would be the case. As the problem of reducing carbon dioxide emissions from transport receives more and more attention, both governments and manufacturers may well show increasing interest in the potential of diesel engines to contribute. Although diesel engines remain significantly more efficient, some much more efficient petrol engines have been developed since 1994; but there is some concern that such engines emit more particulates than conventional petrol engines. **We recommend that increased efforts should be made to develop and bring into general use methods of reducing substantially emissions of particulates and nitrogen oxides from diesel engines. The European Commission should promote this by setting technology-forcing standards for these pollutants.**

8.21 Gas has a similar efficiency advantage to diesel, and the additional advantage of containing less carbon in proportion to its energy content. It also has the great advantage as a transport fuel that emissions of health-related pollutants are lower; and for that reason the Commission has recommended its use as the fuel for heavy vehicles in urban areas. The UK seems to have lagged behind in adopting it as the fuel either for heavy vehicles or for cars (where the size and weight of the tank required is a disadvantage), and in developing appropriate infrastructure.

8.22 Fuel cells using methanol offer another way of using fossil fuels in transport that both safeguards air quality and is more efficient, and is currently attracting great interest. The high power density and energy density of fuel cells make them suitable for use in transport, and a particular advantage over the internal combustion engine is that they achieve a high efficiency over a much wider range of power outputs. Thus, although a vehicle powered by a fuel cell using methanol emits carbon dioxide, the emissions should be less than from an internal combustion engine. Whether there is an overall reduction in carbon dioxide emissions depends on how much energy has been used in producing methanol from fossil fuels, and the source of that energy. Hybrid engines may facilitate the transition to use of fuel cells in vehicles. We describe below the principles on which a fuel cell operates, and discuss the long-term option of relying on hydrogen as the fuel (8.61-8.62).

8.23 Electric batteries eliminate all emissions from vehicles. Despite extensive programmes of research and development on the use of batteries to propel vehicles however, technological progress has so far been disappointing. They still have a relatively low energy density and power density, and take a long time to recharge. A major breakthrough will be needed before battery-powered vehicles can offer a performance and range comparable to those offered by oil-engined vehicles, at reasonable cost. For this reason there is now much more interest in fuel cells as a method of propulsion for vehicles. The overall energy requirement for battery-powered vehicles however might be less than for vehicles powered by fuel cells using hydrogen because of smaller energy losses within the supply chain.

8.24 Liquid fuels for vehicles can be produced from crops. However the production processes can be polluting, and in some cases have a high energy requirement (7.77). To produce biofuels on a large scale a large area of land is needed to grow the crops. It is unlikely that sufficient land could be found for this purpose in the UK, especially if (as seems a more promising approach) large areas of land are to be devoted to growing crops to provide energy in the form of heat. We do not therefore regard biologically produced fuels as a valid option for large-scale use in transport in the UK in the foreseeable future.

8.25 Energy use in international air transport and the resulting emissions of greenhouse gases are not included in national statistics or the limits set as a result of the Kyoto Protocol. Although they so far represent only a small proportion of the global total of carbon dioxide emissions, it should be emphasised that emissions from this source are growing rapidly, and measures to limit their growth are therefore a significant part of the task of countering climate change. All the energy for air transport is provided by oil, and the only theoretical alternative so far identified is hydrogen.

ELECTRICITY

8.26 Demand for electricity is the most rapidly growing component of energy demand.[16] To assess the possibility of alternative patterns of demand and supply for electricity we look at three aspects in turn: increasing the efficiency with which fossil fuels are used in generating plants (8.27-8.31); the options for the UK to obtain electricity from non-carbon sources (8.32-8.41); and the nature of electricity networks and how that is changing (8.42-8.54).

USING FOSSIL FUELS MORE EFFICIENTLY

8.27 There are several approaches to reducing the amounts of carbon dioxide emitted when fossil fuels are used. As we have emphasised, when fossil fuels are used to generate electricity, most of their energy content emerges in the form of low-grade heat. Historically this element was ignored in the UK. The former Central Electricity Generating Board, which had a monopoly in England and Wales, had no legal power to sell energy except in the form of electricity.

8.28 Instead, the objective of more efficient electricity generation was pursued through successive increases in the size of plant used. The very large power stations that resulted produce heat on too large a scale to be a useful resource, and most of those in the UK were constructed on sites remote from potential markets for it. An important criterion for selecting the site for a power station was whether there was sufficient water available to remove the waste heat rapidly. As the amount of water available was often insufficient for direct cooling, perhaps the most conspicuous feature of large power stations became a cluster of giant cooling towers (see photograph II). With an eye to public safety (in the case of nuclear power) or urban air quality (if fossil fuels were used) most large power stations in the UK were constructed on sites remote from other activities which might have a demand for heat. They now stand as monuments to inefficiency and waste.

8.29 If there is to be a very extensive development of CHP schemes, plants generating electricity must be much smaller than in the past. Combined cycle gas turbines (CCGT) (see photograph III) are not only a more efficient technology, but also their efficiency does not increase significantly with size, in contrast to steam-cycle plants. Moreover, generating plants of modest size are more attractive commercially in a liberalised market. There could also be a large-scale development of plants of modest size using alternative carbon-based fuels such as energy crops, as described above.

8.30 Use of gas for electricity generation, in preference to oil or coal, is in any event advantageous because of its lower carbon content. As has been shown already (5.49) the ‘dash to gas’ in electricity generation significantly reduced UK carbon dioxide emissions, although it had other motivations. Coal remains the most important single fuel used in electricity generation.[17] There will not be a large further erosion of its position over the next few years unless there is a change in the government’s current presumption that new gas-fired generating stations should not be built unless there are special circumstances.[18] Government policy on fuel choice for electricity generation is therefore in conflict with the need to reduce carbon dioxide emissions.

8.31 Even with the need to make very large reductions in carbon dioxide emissions we foresee a significant continuing role for fossil fuel plants in providing back-up and flexibility within electricity networks; we enlarge on the reasons for that in the next chapter. The amount of fossil fuels used for that purpose, and hence the carbon dioxide emissions, would not be large. There would be a different position if recovery of carbon dioxide produced at fossil fuel generating plants, and its subsequent disposal in geological strata, becomes established (3.4-3.11). That might happen either because this approach proved to be competitive in cost with alternative energy sources or because the prospective supplies from such sources were not sufficient to meet the expected demand for electricity. In that event, it is likely that, to ensure efficient operation of the processes involved, the generating plants would be very large ones of the kind familiar today, and would operate continuously to supply baseload. It might not be practicable to put to use the very large amounts of low-grade heat that would be produced at a few locations.

ELECTRICITY FROM NON-CARBON SOURCES

8.32 In chapter 7 we considered in turn the potential of a number of energy sources that might provide alternatives to fossil fuels. If fossil fuels are not used for large-scale electricity generation in future, that will create a fundamentally different situation, and it is necessary to consider how various alternative energy sources might be brought together to form a workable system for supplying electricity.

8.33 In the UK, and other countries which do not have large resources of inland water power, nuclear power is the only non-carbon source of energy already in use on a very large scale. It provides energy continuously and operates reliably.

8.34 The present role of nuclear power stations in meeting baseload demand suits their technical characteristics, in that the time needed to start them is long by comparison with fluctuations in demand. There would be scope for a substantial expansion of their baseload role. New designs of reactor may be capable of more flexible operation, and might therefore be able to meet part of the daily variation in demand,[19] although the network would also have to include a substantial capacity of other types of plant with shorter response times.

8.35 The renewable sources that are not carbon-based and that could make a substantial contribution to the UK's future energy supplies are all intermittent rather than continuous. The alternative energy sources that could be continuously available are carbon-based; although they can generate a significant amount of electricity if used in CHP plants, we consider they should be regarded primarily as sources of heat, rather than electricity (8.12).

8.36 The amount of electricity that intermittent sources can be expected to generate on average may be quite a small proportion of their capacity. For present designs of photovoltaic cells the output that can be obtained in the UK is only 17% of capacity. For wave and tidal power it is 33%, and for wind turbines 43% on average.[20]

8.37 The periods when intermittent sources can generate electricity are predictable to a large extent. Photovoltaic cells can operate only during daylight. The timing and height of tides can be predicted accurately a few days ahead. The energy available from wind and waves can be predicted accurately a few hours ahead; and predictions up to three days ahead are probably as reliable as the weather forecasts on which grid controllers already rely to assess future demand for electricity. The periods when intermittent sources are generating electricity however will often not coincide with the periods when demand for electricity is highest.

8.38 The low availability of generating plants using wind, wave and tidal energy can be compensated for to some extent by building a larger number of plants; if these are dispersed over a wide area, local variations in wind speed and sea conditions, and the times of high tide at particular locations, will be much less important. Even if changes in wind speeds were unexpected and relatively sudden, they would not occur simultaneously across the whole country. From time to time however there would inevitably be an overall shortfall in supply in any electricity network which placed heavy reliance on such intermittent energy sources. The energy available from wind and waves is lowest in summer. The greatest problem however might well arise in winter, when demand for electricity is much higher and high pressure could cause cold, still, overcast conditions that can persist over the whole of the UK for several days.

8.39 We discuss below the prospects for developing novel technologies for storing electricity. Unless that can be done, the security of electricity supplies would depend on having other sources of energy available on a substantial scale, so that they could be used, as and when necessary, to meet overall shortfalls in the supply of electricity from intermittent renewable sources.

8.40 Part of this back-up capacity could be provided if the operators of the large numbers of CHP plants we envisage, using alternative fuels (8.11), had the possibility and the incentive to vary the heat-to-power ratio of their plants (8.12) at such times in order to produce more electricity and less thermal energy than would normally be the case. This would be only a partial solution however. A limitation in practice could be that shortfalls in winter in the supply of electricity from intermittent renewable sources might coincide with peak demand for heat.

8.41 A system heavily dependent on intermittent renewable sources would therefore have to contain a correspondingly large capacity of back-up plants using fossil fuels. Although the total capacity of those plants would be substantial, it would be used only infrequently, and the resulting addition to the annual total of UK carbon dioxide emissions would not therefore be large. For some decades, this back-up capacity might be provided by the operators of existing fossil fuel plants, including some of those (mainly coal-fired) already operating in a reserve role. In the longer term new plants would have to be constructed for this purpose. The best prospect for ensuring that, and the most energy-efficient outcome, might be if the operators of CHP plants using alternative fuels were given an incentive to construct supplementary plants burning fossil fuels, which could then be brought into use to generate additional electricity as and when required. They would then be in a position to make the most advantageous use of the low-grade heat resulting from the burning of both kinds of fuel.

FUTURE EVOLUTION OF ELECTRICITY NETWORKS

8.42 In industrialised countries large networks have been constructed to deliver electricity, in the form of synchronised alternating current, from generating stations to users. The existence and nature of these networks has been determined in part by the quest for economies of scale in generation and the locations chosen for the resulting large power stations, and in part by the lack of any efficient method for storing electricity on a large scale, so that it has to be generated at the moment when it is required. An electricity network of this kind is a single vast entity operating in real time.[21] In England and Wales the function of controlling the network is undertaken by the National Grid Co plc, which also owns the bulk transmission system; in Scotland by two vertically integrated companies (Scottish Power plc and Scottish and Southern plc); and in Northern Ireland by Northern Ireland Electricity plc (see box 5A).

8.43 Grid controllers have the task of matching the generation of electricity to demand, which varies considerably according to the time of day, week and year. In England and Wales the minimum demand (which determines the level of *baseload*) is about 20 GW, but demand rises to 50 GW or more at day-time peaks in winter. Within technical constraints, the selection of sources of supply is determined by the prices charged by major power producers (box 5A). Figures 8-I and 8-II show the pool purchase price for each half-hour period during the day, and the large difference between the price for baseload electricity and the prices paid at times of peak demand.

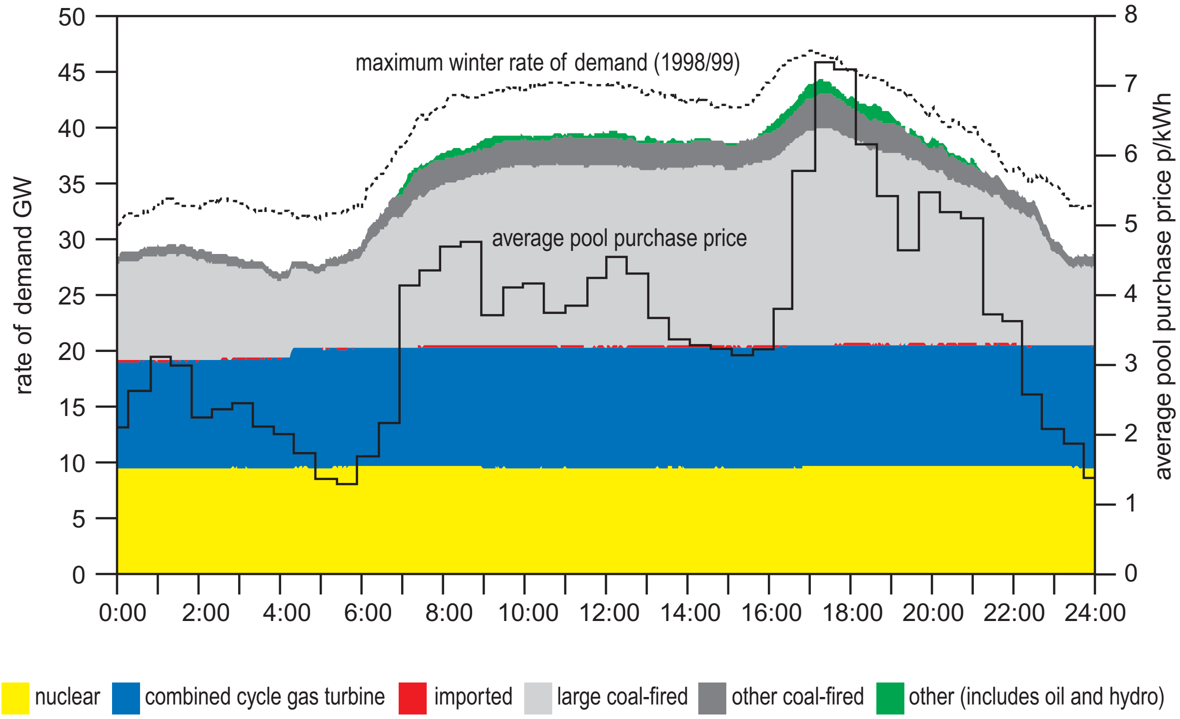
8.44 Figures 8-I and 8-II also show how different types of power station have been deployed to meet demand in England and Wales on a typical winter day and a typical summer day. Baseload is met mainly by nuclear power stations and CCGTs, though with some contribution from large coal-fired stations and electricity imported from France; when demand rises, more use is made of large coal-fired stations, and other coal-fired stations and other types of plant are brought into use. The total capacity of plant available to supply the grid needs to exceed the predicted maximum demand in order to cope with breakdowns and other unexpected eventualities; in the year 1998/99 the margin of surplus capacity was 23%.[22] To ensure reliability of supply, the practice has been to have a capacity of 1.2 GW instantly available.[23]

8.45 Grid controllers also have responsibility for maintaining the quality of supply by keeping variations in voltage and frequency within the increasingly narrow limits acceptable in an economy that depends so heavily on complex electronic equipment. The National Grid Co plc enters into agreements with the operators of suitable generating plants to boost voltage as and when required, to have plant on stand-by in case of breakdowns and other unexpected fluctuations, and to provide a 'black start' capability for initiating restoration of the network if there were to be a total failure.

8.46 One way of obtaining flexibility in the operation of networks is through links with adjacent networks. The grid in England and Wales is linked to Scotland and to France, and the two networks in Ireland are linked. However such links generally have a relatively small capacity; if they are used to import electricity in normal operation, as happens for example with the link to France, they are less useful in responding to unforeseen events.

8.47 The far-reaching changes that have taken place, and are still taking place, in the market for electricity (5.19-5.26) are likely to have profound effects on the nature of electricity networks. The grid in England and Wales was originally controlled by the organisation which generated electricity, but is now controlled by a separate company answerable to its own shareholders. Another consequence of liberalisation and privatisation is a trend towards smaller and more numerous generating plants. The grid controllers cannot have the same close liaison with a much larger number of plants. Moreover the new plants often have more complex relationships with the network, either because they are using intermittent sources of energy

Figure 8-I
Daily pattern of electricity demand, supply and pool purchase price in England and Wales: winter



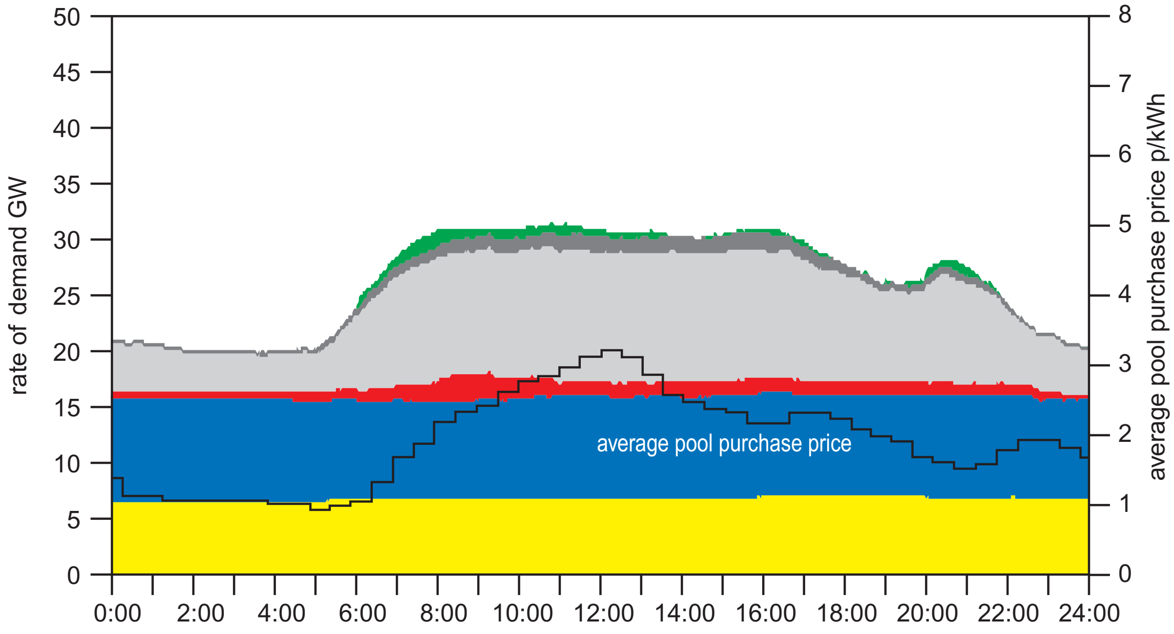


Figure 8-II
Daily pattern of electricity demand, supply and pool purchase price in England and Wales: summer

such as wind power, or because they are CHP plants which may only sometimes be in a position to supply electricity to the network and at other times may wish to take electricity from it.

8.48 The task of managing the national grid in England and Wales will be modified significantly when new electricity trading arrangements come into effect in October 2000. The effect will be to shift some of the burden of ensuring reliability of supply from the grid controllers to the major power producers by imposing heavy financial penalties if they feed into the grid either more or less than the amount of electricity to which they have previously committed themselves. Major power producers will now have an incentive, not only to increase the reliability of their plant, but also to maintain their own reserve plant. The situation in England and Wales will come closer to that in other networks, in which there are usually fewer significant producers.

8.49 The capacity of the bulk transmission system may impose constraints within a network, for example by limiting the transfer of electricity between the midlands and north of England (which have a disproportionate share of generating capacity) and the south. A recent proposal to build an overhead transmission line through Yorkshire, so that maximum use can be made of the link with Scotland, encountered strong opposition because of its effect on the landscape. Another difficulty about heavy reliance on intermittent renewable sources is that a large part of the resource is remote from centres of demand. Much of the wave energy available, for example, is off the west coast of Scotland. If it were necessary to use that to generate electricity to meet demand in England, it has been estimated that the cost of augmenting the high voltage link between the two countries for this purpose would be £400 million.[24] If advantage were also taken of the energy available in the same area from winds and tidal streams, the cost of augmenting the link would presumably be even higher. This does not seem an unacceptably large sum in relation to the total investments that will have to be made in new energy sources and systems, although the cost of strengthening the transmission system, and energy losses in the course of transmission, would affect the relative cost of electricity from the sources in question. A greater difficulty might be public opposition to the construction of new transmission lines through areas of high landscape quality. It remains to be seen whether the development of more efficient cables and less visually intrusive pylons can be successful in reducing such opposition, or whether it might be necessary to incur the considerable additional cost of laying cables underground.

8.50 There are also fundamental changes taking place at the level of distribution systems. Below a certain size, generating plants connect to the distribution system rather than the bulk transmission system. Major growth in *embedded generation* is a necessary concomitant of major growth in CHP plants and in relatively small generating plants using renewable sources of energy. It also has certain inherent advantages: generating electricity at or near the point of use reduces energy losses within the network; electricity is transmitted over shorter distances and undergoes fewer changes in voltage.[25] On the other hand embedded generation adds to the technical difficulties of ensuring security of supply and maintaining the stability of the network, including maintaining an appropriate element of reactive power among end users.

8.51 More radical developments are on the horizon. Small users, including individual households, may come to meet a greater or lesser proportion of their own requirements for electricity from sources of their own. As well as the micro-scale heat and power plants mentioned previously (8.8), another possibility is a significant growth in the use of arrays of photovoltaic cells to provide electricity for individual households. Manufacturers of equipment for these new markets will probably not find it profitable to size them to generate sufficient electricity to meet users' peak demands. To some extent, the gap can be bridged by incorporating storage in the system and/or by automatic disconnection of uses which are less time-sensitive, such as heating and refrigeration. It is probable nevertheless that users of small heat and power plants will want to retain a link to the public electricity network, if only as a precaution against plant failure. It is also possible that such plants will be designed to feed into the public network that part of the electricity generated that is in excess of the user's own requirements. The financial and contractual terms on which they are able to do either of those things will be an important consideration.

8.52 Embedded generation may require a structure for distribution networks which is more interconnected than is generally the case at present. While that is technically possible, it will be more expensive. The amount of electricity passing through the system may be reduced, without necessarily any reduction in peak flows.[26] It may well be necessary to construct more low-voltage transmission lines. Innovative techniques would have to be adopted for maintaining and improving the quality of supply. This might add to costs.

8.53 It has been argued that, because they are intermittent and dispersed, large-scale use of non-carbon renewable sources would complicate the task of controlling the grid to such an extent that, if the proportion of electricity being generated from such sources approaches 20-30%, it would be difficult to maintain frequency and voltage.[27]

8.54 There appears to have been no research as yet into these problems, either by the National Grid or by any other body. **We recommend that the government takes responsibility for promoting, and ensuring sufficient funding is available for, research into technologies that solve the problems of controlling electricity networks in which there is a high proportion of embedded and intermittent generation, and into the economic and institutional issues that will need to be resolved.** The technology for controlling such networks is a field in which the Engineering and Physical Sciences Research Council might well be able to play a key role in stimulating developments.

Energy storage

8.55 The problems of incorporating intermittent sources into electricity networks would be considerably eased if some way could be found of storing the output of generating plants for later use. That would make management of the network much easier and avoid the need for extensive provision of back-up plant (8.40-8.41). What this requires is a technology that enables large amounts of energy to be stored in a form in which it can be rapidly and efficiently recovered in the form of electrical energy. We consider here mechanical storage, using pumped water systems, and chemical storage via hydrogen or electrolyte solutions.

8.56 In the national grid in England and Wales an element of storage is provided already. Pumped storage schemes use water power to generate electricity but, in contrast to direct flow inland water power schemes (7.20-7.21), they operate in a cycle. Low-cost electricity generated in the early hours of the morning is used to pump water up to a top reservoir (see photograph XVI), and electricity is generated at times of peak demand through releasing the water and letting it flow through turbines to a lower reservoir. The time needed to bring it into operation is very short: within 16 seconds it can produce electricity in large quantities (box 8B). The commercial attractiveness of operating pumped storage depends on the relative prices of the electricity used for pumping and the electricity sold from generation; at present the pumping is done with off-peak electricity, largely from nuclear stations, and the electricity generated is sold at peak times. Alternatively this capacity may be invoked to control the stability of the grid as part of the ancillary services for which the operator is paid a price different from the pool price.

8.57 Operation of a pumped storage reservoir involves significant energy losses: only three-quarters of the power needed for pumping is recovered at the Dinorwig and Ffestiniog power stations.[28] When considered as part of a system however, a pumped storage reservoir can be energy neutral because it becomes possible for other plants in the system to operate closer to their optimum efficiency.

8.58 Expanding this method of storing electricity, however, would require construction of large dams and reservoirs on elevated sites; because of the effects these would have on landscape and wildlife, it is unlikely acceptable sites could be found (7.21). Against that background there is considerable interest in developing alternative technologies for storing electricity, even though at the moment there is no experience anywhere in the world of large-scale use of any technique other than pumped storage.

BOX 8B DINORWIG PUMPED STORAGE SCHEME[29]

The pumped storage plant at Dinorwig in north Wales, commissioned in 1983, has six 288 MW turbines with an installed capacity of 1.7 GW[30] and can operate for 5 hours at maximum output. The construction cost at today's prices would be £1 billion. There are no overhead transmission lines from the station, which is inside the Snowdonia National Park.

Dinorwig has three uses: peak lopping and trough filling; system reserve; and load following.

The first use is supply of electricity to the grid at times of peak demand (peak lopping) and use of cheap electricity from the grid between 2.30 am and 4.30 am (trough filling). System reserve capability is used for frequency control and Dinorwig may be asked by the National Grid Company to help keep frequency within 50 Hz +/- 1%. Its capability for load following is called upon when sudden surges in demand for electricity occur, as for example during half-time at major televised football matches. Dinorwig's large capacity and fast response time make it possible to save the large amounts of energy that would be used in keeping coal-fired plants on stand-by to generate for short periods. For example, the capacity of part-loaded steam plant that would have been required to supply demand at half-time during the World Cup game between England and Argentina in 1998 was 5GW.

Dinorwig helps in the more efficient overall use of primary fuel sources by:

- allowing other plants to operate closer to optimum efficiency
- reducing the amount of plant required to be on 'hot' stand-by

resulting in a net saving throughout 1998 at an average rate of 17 MW.

There are also savings in limiting nitrogen oxide and sulphur dioxide emissions. Dinorwig also has greater reliability (99.9%) than coal (80-90%) or CCGT (70-80%).

The availability of Dinorwig increases the efficiency with which other grid plant can be used. ETSU calculated in their 1999 Phase II study that Dinorwig would be energy neutral (electricity consumption at Dinorwig balancing savings from efficient use of other grid plant) if it generated 6.25 GWh/day in 1998/9. This situation will improve with the increased capacity of gas plant, giving a net saving by 2000. This also represents a net saving in sulphur dioxide and nitrogen oxide emissions equivalent to 0.4 and 0.02-0.25% of UK power station output respectively.

8.59 The second general approach is to store energy chemically. One way to achieve this is through use of a transportable *energy carrier;* the distinction between a primary fuel and an energy carrier is explained in box 8C. Hydrogen, the example taken there, is an attractive candidate. It would be used to power fuel cells (see box 8D) which provide an efficient way to convert chemical energy to electrical output, either for supply to the public network or to power vehicles.

8.60 Producing hydrogen in pure form from hydrocarbons (as in the reaction in box 8C) involves significant overall energy losses, although there is the possible advantage that the carbon in the fuel could then be recovered and disposed of in underground strata (3.4-3.11). Alternatively, hydrogen can be obtained from electrical energy by electrolysing water. In an electricity network with a large capacity of intermittent renewable sources, the hydrogen could be produced at times when supply exceeds demand. In the longer term, it is possible in principle that hydrogen could become an internationally traded energy carrier, produced in locations (such as Iceland or Quebec) where renewable energy sources greatly exceed local demand.

BOX 8C **DISTINCTION BETWEEN PRIMARY FUELS AND ENERGY CARRIERS**

The principal constituent of natural gas – one of the main primary fuels – is the chemical compound methane (CH_4). The chemical energy stored is released by reacting the methane to form carbon dioxide (CO_2) and water (H_2O):

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad (1)$$

Alternatively, the energy might be released by some other route such as reforming:

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2 \qquad (2)$$

The hydrogen produced from the primary fuel can then be used as an *energy carrier.*

Energy is released at the point of use by reaction with oxygen, either by direct combustion or by reaction in a fuel cell:

$$4H_2 + 2O_2 \rightarrow 4H_2O \qquad (3)$$

The sum of reactions (2) and (3) is identical to reaction (1), and the overall energy release from reactions (2) plus (3) is identical to that from reaction (1). Reaction (2) actually absorbs heat (usually provided by burning a fuel), so that hydrogen is a particularly intensive energy carrier. Given that there are thermal inefficiencies in the processes carrying out the reforming reaction however, the net energy released in practice by using the energy carrier through reaction (3) is less than the energy released by burning the primary fuel plus the theoretical energy absorption by reaction (2).

8.61 Hydrogen stored on a large scale under appropriate conditions represents one of the most efficient ways of storing energy. However, fuel cells are best suited to producing electricity on a relatively small scale (up to a few MW). Rather than using hydrogen for centralised storage to be recovered as electrical output to the grid therefore, a more plausible concept is that hydrogen would be distributed as an energy carrier into decentralised stores or as a transport fuel. Its advantage over electrical batteries, another form of decentralised storage or power for transport, is that it provides a much higher intensity of energy storage.

8.62 For the time being it is likely that extensive use of fuel cells will be based on producing hydrogen at the point of use from either a fossil fuel (gas) or a hydrogen-rich fuel manufactured from fossil fuel (methanol). The former route will be used for fuel cells providing heat and power for buildings (8.8), for which gas can be obtained from the existing distribution network); the latter route for vehicles, in that it requires only small modifications to the technology used to distribute petrol and diesel (8.22). Eventually however it will be necessary to obtain hydrogen by other means.

8.63 There is also a need, reflected in keen interest in the electricity industry, for other technologies for large-scale centralised chemical storage of energy in a form from which

BOX 8D **FUEL CELLS**

A fuel cell utilises a chemical process to convert hydrogen or a hydrogen-rich fuel stream into electrical energy and heat. It can do so with high efficiency (i.e. high efficiency of conversion of fuel to useful energy), producing a stable (DC, non-fluctuating) power output. Most fuel cells operate with high power densities, that is, they produce a high power output per unit weight, volume or area. Different types of fuel cell are distinguished by their use of different electrolytes and the different temperatures reached during operation. Some of the range of fuels used in fuel cells could be supplied by renewable sources, which would promote diversity in energy supply and a transition to renewable energy sources.

There are limitations to fuel cell performance which mean that the *theoretical* cell voltage cannot be utilised entirely; these include the oxygen deactivation barrier at the cathode and mass transport problems caused by the diffusion of gaseous species and water through the cathodes, electrolyte and any catalyst layers in the fuel cell. Only about half of the energy of reaction (hydrogen + oxygen → water) can be converted into useful electrical energy. These limitations mean that a typical single fuel cell will have an area of about 50 cm^2 and a potential difference across it of about 0.7 volts. Generation of a usable voltage requires a fuel cell system to be built up of a stack, or several stacks, of cells, the anode of one cell being in contact with the cathode of another, and so on.

One of the principal advantages of fuel cells is that they display high efficiency across their output curve. The internal combustion engine (ICE) has a point of maximum operating efficiency, usually at high revolutions, either side of which it is less efficient. The fuel cell, in contrast, has a comparatively flat efficiency curve, and is generally more efficient operating at below 100% of its rated power. Although not a particularly important factor in stationary applications, in transport the engine of a vehicle is rarely at its ideal operating speed and the efficiency gain of a fuel cell vehicle over an ICE vehicle is much greater during a drive cycle than during continuous tests.

The main disadvantage of fuel cells is the large number of ancillary units which are required to deliver large scale power generation from fuel cells. The ancillary equipment includes fuel supply and water removal pipes, metering instruments, fuel reformers, pumps, compressors, and heat exchangers. Each of these ancillary systems will have a parasitic load which reduces the efficiency of the overall system. Fuel cells that are running are impressive in terms of reliability of performance but the *balance of plant* (BoP) that makes up the rest of the system means that, at present, a 200 kW phosphoric acid fuel cell generating unit is several times the size of a similar power diesel or natural gas CHP unit. The size of generating system is important in stationary applications but paramount in mobile systems where the power (or energy) density of the package rather than the fuel cell in isolation must be considered.

electrical energy can be recovered. Key factors in assessing such technologies are the cost, reliability and life of the installations; the risks they would pose to workers and the public; the capacity and efficiency of energy storage and recovery; and the rates at which electrical energy could be transformed to stored chemical energy and (more particularly) recovered again. One approach, based on regenerative fuel cell technology, is sufficiently promising that National Power has announced plans to build a 10 MW demonstration unit. It is described in box 8E.

8.64 Other means of storing energy have been proposed, but are at a much more speculative stage. Superconducting magnetic energy storage systems are devices based on the principle of storing energy by an electric current introduced into a resistance-free superconducting coil. The superconductor must be maintained at cryogenic temperatures, around −269°C (liquid helium) or −133°C (liquid air) depending on the type of superconductor. Devices using this principle however are extrapolations from laboratory observations, and are a long way from demonstration of technical or economic viability. It would be unsafe to assume that they can be developed and applied on a large scale by the middle of the century.

8.65 In our assessment, this leaves hydrogen and regenerative fuel cells as the technologies which could be in widespread use by the middle of the 21st century, but with rather different

BOX 8E ENERGY STORAGE USING REGENERATIVE FUEL CELLS[31]

Innogy Limited, part of National Power's UK division npower, is planning to construct a 360 GJ installation using a technology called 'Regenesys'. This facility will be the largest energy storage plant of its type in the world. It will have a rated power output of 15 MW, which can be fed directly into the electrical distribution grid. Start-up time from complete shutdown is expected to be rapid. When running, the plant should be capable of switching from fully charging to fully discharging in about 20 milliseconds. Conversion of electrical to stored chemical energy can be repeated with high recovery efficiency.

Energy is stored chemically in two concentrated aqueous electrolyte solutions, of sodium bromide and of sodium polysulphide. The electrolytes are pumped through a regenerative fuel cell in which they are separated by an ion-selective membrane. The membrane is permeable to sodium ions but not to the anions present. A simplified overall chemical reaction for the cell is:

$$3\ \mathrm{Na\,Br} + \mathrm{Na_2\,S_4} \underset{\text{discharging}}{\overset{\text{charging}}{\rightleftarrows}} 2\ \mathrm{Na_2\,S_2} + \mathrm{Na\,Br_3}$$

On charging, the bromide ions are oxidised to bromine which is complexed as tribromine ions, while sulphur in the polysulphide anion is converted to sulphide ions. On discharging, the sulphide ion acts as the reducing agent and the tribromide ion as the oxidising species. After charging, each cell gives a potential difference up to 1.5V. Cells are linked in series electrically, with electrodes shared between two cells, to generate the required total potential difference.

In addition to the 'Regenesys' fuel cells, the plant requires a power conversion system to act as the interface between the alternating 33 kV grid, and the DC fuel cells. However, the whole plant is compact, occupying less than half a hectare and housed in a low-rise building.

applications as explained above. In view of the uncertainty over their deployment however, we have taken a conservative approach in constructing scenarios for possible UK energy systems in 2050, by assuming that large-scale energy storage will not be available and that hydrogen will not be traded internationally as an energy carrier. We have taken the alternative approach of incorporating supplementary generating plant to the extent required to back-up supply from intermittent renewable sources. Availability or otherwise of energy storage primarily affects the back-up capacity needed, with much less effect on the overall energy balances which are the principal topic of chapter 9. Even though the scenarios have been constructed assuming no large-scale energy storage, we nevertheless regard it as very important that work to develop such technologies should be pressed forward and given a high priority. **We recommend that the government promote research and development into new technologies for large-scale energy storage, possibly on a collaborative basis in Europe.**

> ***There is a vast, largely untapped opportunity for utilising the heat which is wasted when electricity is generated. Exploiting this heat will require the growth of heat networks and a shift from very large, all-electricity plant towards smaller and more numerous combined heat and power plants. The electricity distribution system will have to undergo major changes to cope with this development and with the expansion of smaller scale, intermittent renewable energy sources. The transition towards a low-emission energy system would be greatly helped by the development of new means of storing energy on a large scale***